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GENERALIZED STRUCTURAL INTEGRITY ASSURANCE TECHNOLOGY: APPLICATION TO ARMY GENERIC STRUCTURAL INTEGRITY ASSURANCE TECHNOLOGY PROGRAM

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MATERIEL DURABILITY BRANCH

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ABSTRACT

A generalized structural integrity technology concept is presented which defines structural integrity parameters for resistance to maximum loading and service life which must be evaluated on the basis of an integrated qualification testing and in-service program by acceptance criteria formally specified by the particular hardware system authority. A service life base line parameter is defined which characterizes the nominal behavior of a system. A service life design sufferance parameter is defined and illustrated which characterizes "other than nominal" conditions which are a major influence on safety. Design sufferance conditions are general and may involve damage tolerance or any other design conditions which may deviate from base line conditions. Limited duration service life unrepaired/repaired damage parameters are defined for those unique design conditions. The application of this generalized concept to an Army Generic Structural Integrity Assurance Technology Program covering tasks of design information, analyses and material characterization, design development testing, qualification testing, and life management data and life management implementation is discussed. The benefit of a formal disciplined technology program in promoting structural integrity in the arena of innovative design with emerging materials is cited.

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INTRODUCTION

Structural integrity assurance, in the context of this report, is the assurance that the critical load-carrying components of a structure do not fail in the service environment during a specified lifetime. The term "structural integrity" does not appear in classical design using strength of materials where the focus of attention is on calculations of mechanics parameters and their evaluation in terms of associated failure criteria. These comparisons include allowances for uncertainties, or safety factors, which are often quite large. Design for fatigue conditions is usually concerned with infinite life based on endurance limit criteria. In general, there is no direct connection between in-service maintenance and inspection and strength of materials issues. The design and usage of lightweight, finite life structures, such as some aircraft components with minimal safety factors, gives considerable attention to additional issues related to qualification testing and in-service inspection and maintenance. Formalized "structural integrity programs" have been developed for a few specific applications to establish proper detailed activities and interrelationships between structural design, qualification testing, and in-service maintenance and monitoring. A notable program is the Air Force Structural Integrity Program.[1,2] However, most hardware system structures are developed using ad hoc measures significantly influenced by the previous experience base for similar structures which typically includes several implicit factors such as those considered later in this report.

INNOVATIVE SYSTEM DEVELOPMENT - STRUCTURAL INTEGRITY

It is expected that new system development will emphasize innovation and ingenuity in order to achieve system performance goals.[3] Detailed "how to" design requirements would be prohibited in order to encourage the development of new functional systems using emerging materials. It must be assumed that the users of such advanced functional systems would expect that the structural integrity (SI) of critical components would be assured. The absence of an experience base for the functional system, the material, and related design methods creates precisely an arena where a clear understanding by the particular hardware system authority and the system developer of structural integrity assurance (SIA) principles, fundamentals, and specific details is needed in order to achieve and document SI for the system. This need can be met by a formal Generalized Structural Integrity Assurance Technology Program which covers the overall scope, interrelation of tasks, and specific detailed issues which must be addressed. The proposed requirement to demonstrate the structural integrity of any innovative design using a formalized program outlining the basic principles of SIA to promote understanding of critical issues does not infringe upon the legitimate exercise of ingenuity by a system developer.

APPLICATION TO ARMY MATERIEL SYSTEMS

The U.S. Army has no formal broadly applicable structural integrity requirement. Within the Army Materiel Command, several major subordinate commands deal individually with SI issues related to systems under their command. Materiel systems in which SI deficiencies could cause serious failures include helicopters, missiles, gun tubes and projectiles, vehicles, bridging, and large-scale antennas. The only formal structural design requirements in use are the Aviation Command Aeronautical Design Standards. Technical specialists within the Aviation Command have advocated the development of a formal helicopter structural integrity

1. *Airplane Structural Integrity Program, Airplane Requirements.* MIL-STD-1530A, 11 December 1975.
2. *General Specification for Aircraft Structures.* MIL-A-87221 (USAF), 28 February 1985.
3. CRAWFORD, C. *Performance-Oriented Specifications: How Big is the Hidden Challenge.* Vertiflite, v. 31, no. 5, 1985.

program.[4,5] A National Materials Advisory Board study of SI issues in the Army[6] concluded that "a formal structural integrity program would be highly desirable in Army system development and procurement." The study also recommended "the development of a standard defining a structural integrity program considered as generic for all Army equipment." The generalized SIA approach described subsequently is intended to meet the goal of a program which is generic for all Army equipment. A fully detailed formalized Structural Integrity Assurance Technology Program for the Army is in preparation.*

PRELIMINARY OBSERVATIONS

It is useful to consider the following issues before describing the generalized SI program: the interface between SI technology and hardware system development, and the inherent nature of modeling and qualification testing tasks in SI programs.

All SI activities in design and testing (sizing of parts, material selection, service life predictions) directly impact overall system issues such as performance, downtime or readiness, cost, scheduling, as well as safety. These hardware system issues are the responsibility of the hardware system development authority. In view of the integrated relationship between SIA and major system issues, SI methods and criteria cannot be specified at the generic level by structural specialists. These SI specifications are major system-related decisions which must be made by integrated staff and management of the particular hardware system development authority. Therefore, a useful generalized approach should provide a fundamental SI framework within which specific decisions are made by the particular hardware system authority.

The selection of a structural analysis model is a critical activity associated with hardware development within the SIA technology program. The selection depends upon the **engineering judgement** of the specialist. The specialist must consider an extensive range of issues including: material ("quality," ductility, toughness, strength, stiffness, variability, and constitutive relationships), loading (amplitude, distribution, rate, cyclic, and transient time variations), environment (temperature, humidity, corrosive media, and solar energy effects), in-service damage, failure theories, and the size scale of their application, factors of safety, service life scatter factors, the nature of in-service inspection, and the nature of the qualification test program. When the model is selected to represent the behavior of a portion of the structure, issues not accounted for by the model are likely to be permanently excluded from direct consideration in the structural integrity program. Such issues are not likely to play a role or be "covered by" qualification testing, as will be discussed subsequently. For example, some very high strength metals have quite low resistance to the advance of a sharp crack in the presence of corrosive media as measured by linear elastic fracture mechanics parameter K_{IEAC} (or K_{ISCC}). If a nonflaw based model; i.e., a safe life model, is adopted for analysis, the possibility of the occurrence of crack advance in corrosive media will be excluded from consideration throughout the SI program even though this behavior can occur in very high strength metals if very small cracks are introduced, either initially or in service.

Qualification tests are not, in general, reproductions of actual service life. In practice, qualification tests may be quite artificial. The practical requirements are such that the time

*MATTHEWS, W. T. *A Generic Structural Integrity Assurance Technology Program for the Army.* U.S. Army Materials Technology Laboratory, MTL TR, to be published.

4. IMMEN, F. H., and ANDERS, W. L. *Integration of Nondestructure Testing Methods Into Design for Structural Integrity Assurance.* J. of the American Helicopter Society, v. 25, no. 2, 1980.

5. SPIGEL, B. *Foundations of an Army Helicopter Structural Integrity Program.* American Helicopter Society National Technical Specialists Meeting on Advanced Rotorcraft Structures, Williamsburg, VA, October 1988.

6. *Assuring Structural Integrity in Army Systems.* National Material Advisory Board, National Research Council, NMAB-117, February 1985.

duration must be drastically compressed, the loading spectrum modified and truncated, load-time effects are simplified and idealized, environmental effects are usually simulated by loading changes, and often no specific in-service damage is directly introduced. A single or a few units are tested to represent the entire system population, and test durations and load levels are adjusted accordingly by the application of safety factors and service life scatter factors. The many adjustments and idealizations are made based in large part upon modeling choices selected initially along with input from design development testing and from the experience data base. When tests are completed, the interpretation of results such as the significance of "small" damage, the performance of design concepts (structural redundancy, damage arrest or containment, and damage detection systems) may be uncertain in view of the influence of the many adjusting factors and simulations. The interpretation of qualification tests may be strongly biased by the initial modeling choices since many of the factors and simulations may have been derived on the basis of this modeling.

The Generalized SIA Technology Program, outlined in the following section, addresses these issues: the interrelationship with the overall hardware system development, modeling choices, and qualification testing.

OUTLINE OF GENERALIZED SIA TECHNOLOGY PROGRAM

The program is composed of five major tasks, similar to the Air Force program, as outlined in Table 1. The major tasks are organized according to the sequence in which they are most likely to be performed throughout the system life cycle. No strict ordering of tasks and subtasks is intended, and other arrangements would be possible. The major tasks are design information, design analyses and material characterization, design development testing, qualification tests and life management data, and life management. The life management task comprises the collection and interpretation of in-service information related to SIA and the initiation of SIA actions for hardware systems in service. The SIA technology program outlined in Table 1 is applied to critical parts only. The program would be specialized by the hardware system authority for particular systems using only those portions of the program which are appropriate. Generalized SIA is a framework which requires the particular hardware system authority to specify, establish, and document related details and acceptance criteria. The generalized SIA concept defines a set of parameters which characterize SI. The generalized SIA concept also provides guidelines for the specification of detailed parameters, criteria, and methods which lead to the results necessary to evaluate SIA of a hardware system on the basis of acceptance criteria specified by the particular hardware system authority. The authority has wide flexibility in specifying methods, but must document the rationale for specifications in order to ensure appropriate interrelation of tasks and to clearly understand the limits of application of the methods. Generalized SIA features are as follows.

Structural Integrity Characterization (Task I-B)

The SIA of a hardware system is characterized by the following structural integrity parameters which must, in general, be addressed in all major tasks:

- The resistance to maximum loading SI parameter measures and their limiting criteria must be defined by the particular hardware system authority: yielding, ultimate strength basis, buckling, excessive deformation, elastic, or elastic plastic fracture.

Table 1. GENERALIZED STRUCTURAL INTEGRITY ASSURANCE TECHNOLOGY PROGRAM

Task I Design Information	Task II Design Analyses and Material Characterization	Task III Design Development Testing	Task IV Qualification Tests Life Management Data	Task V Life Management
A. SIA Plan	A. Max. Load Analysis	A. Service Load and Environment	A. Max. Loading Resistance	A. SIA Management
B. SI Characterization - Max. Loading Resistance - Service Life - Base Line - Design Sufferance - Limited Duration Service Life	B. Service Load Analyses	B. Joints-Mechanical Tests	B. Service Life - Base Line - Design Sufferance	B. Operation Envelope Implementation
C. Design for SIA	C. Chemical/Thermal Environment	C. Building Block: Advance Material Testing	C. Limited Duration Service Life	C. Life Maintenance Implementation
D. Service Life SIA Plan	D. Mechanical Properties Characterization	D. Max. Loading Resistance	D. Qualification Test Summary	D. In-Service Usage Monitoring
E. Design Service Life and Design Usage	E. Mechanics Analyses	E. Service Life - Base Line - Design Sufferance	E. Life Management Data Package - Manufacturing Quality Control Summary - SI Analysis Summary - Operational Envelope - Life Maintenance Plan - In-Service Monitoring Plan	E. In-Service SIA Data Bank: Feedback to Analysis Summary
F. Materials, Processes, Joining Methods Selection	F. SIA Analyses at Max. Loading	F. Limited Duration Service Life	F. SIA Evaluation	
	G. Service Life Analyses - Base Line - Design Sufferance	G. Manufacturing Quality Control Summary		
	H. Limited Duration Service Life Analyses/Survivability			

- The service life base line design SI parameter characterizes, for each critical component, the vast majority of its total number in service. This characterization is associated with fulfilling the service life requirements of the system. This parameter represents a limiting characterization of nominal design conditions. The particular hardware system authority must define service life failure in terms of failure criteria and extent of damage in relation to design concepts previously cited.
- The service life design sufferance SI parameter characterizes "other than nominal" issues such as the capacity to endure conditions which deviate from the base line model conditions. These deviations may involve more extreme conditions within the same basic model used for base line design or those associated with a different model. For example, the base line design may be based on a nonflaw (safe life) model, while the design sufferance model might be a flaw-based (damage tolerant) model. The term "design sufferance" is chosen to encompass a broad range of potential issues, including damage tolerance and issues such as loss of near surface conditions which inhibit crack or damage initiation and growth (such as favorable residual stresses) or which provide environmental protection of metallic or nonmetallic structures. Environmental protection may be lost through damage in service or during maintenance. Additional issues for design sufferance modeling may include unintended out-of-plane loading of tailored or engineered materials or extreme undetected impact damage of advanced materials and multiple site, wide scale damage and degradation.
- The limited duration service life unrepaired damage SI parameter characterizes structural integrity under unique conditions associated with a specified very short duration

of service with specified unrepaired damage. The conditions are related to completing a single-usage cycle or mission; i.e., "returning home," presumably with restricted usage and reduced loads. The design conditions of particular interest would be crack or damage behavior and modified environmental conditions within the structure.

- The limited duration service life repaired damage SI parameter characterizes SI for an additional set of special conditions associated with temporary repair for a specified limited duration until permanent repair is performed at a major facility. The design conditions may involve less severe usage and the consideration of joints between repair and nominal structure and modified environmental conditions within the structure.

Designing for Structural Integrity (Task I-C)

Flexibility in methods is permitted while emphasizing that the entire design, analysis, and qualification process must consider directly the nature of in-service monitoring, maintenance, and inspection as a major issue influencing the design.

Service Life SIA Plan (Task I-D)

A critical parts list must be established by the hardware system developer. The Generalized SIA Technology Program is required only for critical parts.

Analysis Methods (Task II)

Flexibility is permitted, supported by documented rationale, based on issues such as material characterizations.

Building Block Advanced Material Design Development Testing (Task III-C)

This is a testing approach to develop design characterization where general analytical methods for dealing with configuration complexities, environmental conditions, material characterization, and property variability of advanced materials is lacking. The process involves a series of tests of increasing geometric complexity (coupons, elements, subcomponents, and components). Specific issues are investigated and presumably resolved, perhaps by statistically based testing, at the smallest testing scale possible, leading, finally, to one or a few tests of component size which investigate complex configuration issues only. The rationale supporting resolution of specific issues must be documented to support the application of results for qualification testing and evaluations and to understand the application of results to life management actions. This documentation, related to the use of advanced materials, is one of the principal benefits of the formalized, disciplined generalized SIA technology program.

Qualification Testing (Task IV)

Full size testing is required, in general, consistent with modeling methods, for all SI parameters to permit proper evaluation relative to hardware system goals and to validate analyses. If the modeling is flaw or damage based, the qualification testing must involve structure with specified flaws or damage.

Structural Integrity Analyses Final Summary (Task IV-E)

This is the subtask in which all of the Generalized SIA Technology Program documentation requirements for modeling, analysis, supporting data, and rationale are summarized.

Life Maintenance and In-Service Monitoring Plans (Task IV-E)

These plans must be based directly on SI parameter modeling, analysis, and qualification test results. In-service monitoring is required to establish actual hardware system usage which can be used to update analyses and modify life management actions.

Structural Integrity Assurance Evaluations (Task IV-F)

The **evaluation** of SI parameters must be based on a consideration of **all** of the following: result of qualification testing, a coordinated in-service monitoring and maintenance program directly related to SI parameters, and a validated, documented analysis.

General Requirements

The particular hardware system authority is required to specify details of SI methods and criteria which are critical for implementation of a disciplined SI program and to document their bases and supporting rationale. The following shall be specified: modeling methods, failure criteria or limiting values of measures of SI parameters, factors of safety for analysis and test, basis for usage definition and service life loading levels (nominal or extreme), load spectrum or sequence effects, basis for characterizing service life (for qualification testing, in-service maintenance, and monitoring), initial or in-service flaw or damage characterization, statistical basis for material properties, and treatment of environmental and dynamic loading effects. If it is not feasible to specify appropriate values for specific designs or classes of hardware systems, the hardware system developer shall establish values and document supporting data and rationale.

DISCUSSION

A major feature of the program is the integration of all pertinent SIA issues, including important issues which typically are not explicitly considered in SIA programs. Such implicit issues include: whether material defects (which occur in all materials) shall be explicitly considered, the significance of yield or ultimate strength failure basis in relation to the consequences of structural failure, the precision of loading information (spacial distribution, magnitude - nominal/extreme, and time variations), the basis for safety factor and scatter factor choices, the extent of undocumented abuse which the structure is expected to endure, and the effect of in-service maintenance and inspection capability limitations upon design and modeling choices.

Another major feature of the generalized SIA concept is the broad characterization of "other than nominal" issues which may impact service life by the service life design sufferance SI parameter. The selection of design sufferance issues and modeling rests primarily upon engineering judgement. Such judgement is a significant component of all hardware design development. Design development testing provides an opportunity to assess the relative significance of alternative choices of design sufferance conditions prior to qualification testing.

The intent of this aspect of generalized SIA is to require consideration of those "other than nominal" conditions known to occur in hardware systems[7] which have a significant influence upon safety. The approach requires that initial or in-service conditions, primarily those

7 McCARTHY, J. F., TIFFANY, C. F., and ORRINGER, O. *The Application of Fracture Mechanics to Decisions on Structural Modifications of Existing Aircraft Fleets.* Case Studies in Fracture Mechanics, U.S. Army Materials Technology Laboratory, AMMRC MS 77-5, June 1977.

related to material "quality" shall be analyzed and tested; for example, if a structural design involved a large-scale, stiffened, riveted metallic structure, then a damage tolerance modeling approach with initial quality and analysis methods as specified by the Air Force standards would appear to be the most appropriate approach. For other designs, the development and application of alternative approaches such as Cardrick, Maxwell, and Morrow[8] and Weaver[9] would be encouraged within the framework of the generalized program.

The generalized SIA requirement for complete evaluation of defined SI parameters can be useful even if a pass/fail criterion is not established for the design sufferance parameter by the particular hardware system authority. The evaluation can provide guidance for necessary in-service maintenance and can clarify design choices, as illustrated by the following hypothetical hardware design.

A component is to be designed for a fatigue life requirement of 5,000 primary use cycles. The service life base line design SI parameter is modeled on a nonflaw basis. Two candidate materials, A and B, are being considered; material A is more expensive. The base line fatigue evaluation results indicate that designs using both materials are qualified for 5,000 use cycles of service life. The design sufferance SI parameter evaluation is based on a flawed model for which an initial quality size limit of 0.25 mm is established. The evaluations of the design sufferance parameter for designs using each material indicate that material A is qualified for 2,500 use cycles and material B is qualified for 1,000 use cycles. This design sufferance evaluation provides useful information to clarify design choices and guidance, directly related to SI characterization, for proper in-service maintenance and inspection. Also, in this hypothetical case, the analytical estimates of fatigue life were found to be about 50% of the actual qualified life. In this case, the qualification tests provide data used as guidance in modifying the analysis to provide SI characterization which is suitable for life management actions.

The documentation of validated analyses (Task IV-E) is required to support life management actions (Task V). Experience has shown that hardware system usage may differ from original estimates and that the stress spectrum used for development and qualification may contain errors.[10] In addition, life management programs may require planned mission changes, structural modifications, and life extension programs. A validated, documented analysis would permit initial assessment of such issues. Substantive structural changes must be qualification tested to verify analytical assessments.

Formal specification of SI-related quantities is needed for clarity in program implementation since a variety of interpretations of such quantities is possible, as illustrated by the survey of international airworthiness authorities concerning factor of safety.[11]

It is recognized that completely satisfactory technical methods may not be immediately available for detailed strength, stiffness, and fatigue analyses of innovative designs using advanced materials. Interim methods will be used. It is important to document interim design development methods with respect to formalized SIA guidelines in order to understand the limitations of interim methods.

8. CARDRICK, A., MAXWELL, R., and MORROW, S. *The Application of Fatigue Damage Tolerance Concepts to Helicopters: The Approach Proposed by the U.K. Military Airworthiness Authorities.* Proceedings of the American Helicopter Society Specialists' Meeting on Fatigue, St. Louis, MO, October 1984.
9. WEAVER, R. T. *Substantiation of Damage Tolerant Designs in Civil Helicopters.* American Helicopter Society Annual Forum, 1987
10. LINCOLN, J. W. *Damage Tolerance - USAF Experience.* Proceedings of the 13th Symposium of the International Committee on Aeronautical Fatigue, Engineering Materials Advisory Service, U.K., Pisa, Italy, May 1985.
11. *Factors of Safety Related to Structural Integrity.* Advisory Group for Aerospace Research and Development, NATO, Report No. 677, 1981

BENEFITS OF FORMAL GENERALIZED SIA TECHNOLOGY PROGRAM

This formal SIA technology program promotes fundamentally sound hardware development with technical consistency in modeling, analysis, and testing methods and their interpretation. The technology program promotes early discovery of SI deficiencies by providing a "check list" which diminishes the possibility of inadequate consideration of issues within the array of various technical disciplines and tasks, improved design based on parameters directly related to SI, and improved understanding of SI issues between hardware system authorities and developers. A formal documented program is expected to be particularly beneficial in the development of innovative systems where the data base of previous experience is lacking.

A formalized design sufferance parameter requires consideration of interdisciplinary issues which may significantly influence failure in innovative designs which are not normally considered by structural specialists.

A documented technology program clarifies the state-of-the-art of SI technology providing guidance for research and advanced development, including demonstrator programs. A formalized program, with its generalized framework and associated standard terminology, promotes technology transfer between users: e.g., Army Major Subordinate Commands. In addition, communication would be improved between hardware system authorities and developers (contractors) within large hardware developer organizations, and between contractors involved in joint development of large systems.

SUMMARY

1. A generalized structural integrity assurance technology program has been presented which is composed of *five major tasks from "cradle to grave"* which illustrates the features and benefits of such a program.

2. Generalized SIA characterizes the structural integrity of hardware systems on the basis of several SI parameters relating to the resistance to maximum loading and service life.

3. The generalized SIA Technology Program is required for critical parts only.

4. Generalized SIA requires **evaluation** of these SI parameters involving the results of all tasks on the basis of acceptance criteria formally specified by the particular hardware system authority.

5. The service life design sufferance SI parameter is introduced which characterizes the influence of a wide range of "other than nominal" conditions upon safety.

6. Flexibility in devising SI methods is encouraged.

7. Detailed SI criteria must be defined by the particular hardware system authority and supporting basis and rationale must be documented.

8. The building block design development method for advanced materials is formalized within the program framework.

9. Analyses must be validated and documented.

10. In-service data bank and reporting system must be established to document system in-service condition and for feedback to support life management actions.

11. The benefits of the SI program for innovative hardware system design is emphasized.

12. Potential application of the generalized program to Army materiel development is cited.

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GENERALIZED STRUCTURAL INTEGRITY ASSURANCE TECHNOLOGY: APPLICATION TO ARMY GENERIC STRUCTURAL INTEGRITY ASSURANCE TECHNOLOGY PROGRAM -
William T. Matthews

Technical Report MTL TR 89-88, September 1989, 10 pp-table, D/A Project: 1L161102.AH42

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Key Words

Structural engineering
Structural mechanics
Mechanical properties

A generalized structural integrity technology concept is presented which defines structural integrity parameters for resistance to maximum loading and service life which must be evaluated on the basis of an integrated qualification testing and in-service program by acceptance criteria formally specified by the particular hardware system authority. A service life base line parameter is defined which characterizes the nominal behavior of a system. A service life design sufferance parameter is defined and illustrated which characterizes "other than nominal" conditions which are a major influence on safety. Design sufferance conditions are general and may involve damage tolerance or any other design conditions which may deviate from base line conditions. Limited duration service life unrepaired/repaired damage parameters are defined for those unique design conditions. The application of this generalized concept to an Army Generic Structural Integrity Assurance Technology Program covering tasks of design information, analyses and material characterization, design development testing, qualification testing, and life management data and life management implementation is discussed. The benefit of a formal disciplined technology program in promoting structural integrity in the arena of innovative design with emerging materials is cited.

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